Dynamic Adjustment of Irrigation Technology/Water Management in Western U.S. Agriculture: Toward a Sustainable Future

Glenn D. Schaible,[1] C. S. Kim[2] and Marcel P. Aillery[3]

[1]*Agricultural Economist, Resource & Rural Economics Division, Economic Research Service, U.S. Department of Agriculture, 1800 M Street, NW, Rm. S4048, Washington, DC, 20036-5831 (corresponding author: phone: 202-694-5549; fax: 202-694-5775; e-mail: Schaible@ers.usda.gov).*
[2]*Senior Economist, Resource & Rural Economics Division, Economic Research Service, U.S. Department of Agriculture, 1800 M Street, NW, Rm. S4047, Washington, DC, 20036-5831 (phone: 202-694-5545; fax: 202-694-5775; e-mail: CKim@ers.usda.gov).*
[3]*Agricultural Economist, Resource & Rural Economics Division, Economic Research Service, U.S. Department of Agriculture, 1800 M Street, NW, Rm. S4204, Washington, DC, 20036-5831 (phone: 202-694-5511; fax: 202-694-5776; e-mail: MAillery@ers.usda.gov).*

Changing water demands induced through climate change and a growing biofuel energy sector throughout the western States are expected to increase pressures on the present allocation mechanisms for an increasingly scarce resource, raising uncertainty about the sustainability of irrigated agriculture in the West. In this paper, we first present the policy motivation for examining continued producer adoption of water conserving irrigation production systems as a foundation for providing a sustainable future for western irrigated agriculture. Second, we summarize the historical transitions that help to define the adjustment path to increased sustainability for the sector. While western irrigated agriculture is on a path toward greater sustainability, evidence suggests that the sustainability goal has not been fully attained. Third, we develop a new conceptual framework for groundwater management that endogenizes both per acre applied water and an acreage-based technology adoption relationship within a normative, dynamic-optimization model for groundwater irrigated agriculture. The framework models producer adoption decisions under uncertainty while accounting for the influence of irrigation technology as a quasi-fixed input, i.e., the influence of asset fixity on producer adoption decisions. In this model, total crop production is based on consumptive use of irrigation water while the cost side is based on total applied water.

L'évolution de la demande en eau que suscitent le changement climatique et l'essor du secteur des biocarburants dans l'Ouest américain devrait faire monter les pressions sur les mécanismes actuels d'allocation d'une ressource de plus en plus limitée, soulevant ainsi de l'incertitude quant à la viabilité de l'agriculture irriguée dans cette région. Dans le présent article, nous avons tout d'abord présenté la motivation politique pour examiner l'adoption soutenue, de la part des producteurs agricoles, de systèmes de production irriguée axés sur l'économie de l'eau comme élément permettant d'assurer un avenir durable pour l'agriculture irriguée. Nous avons ensuite résumé les transitions historiques qui aident à définir les mesures à prendre pour accroître la viabilité du secteur. Bien que l'agriculture irriguée dans l'Ouest américain soit sur la voie d'une viabilité accrue, les données disponibles autorisent à penser que l'objectif de la viabilité n'a pas été pleinement atteint. Enfin, nous avons élaboré un nouveau cadre conceptuel pour la gestion de l'eau souterraine qui endogénise le lien entre l'eau utilisée à l'acre et l'adoption d'une technologie fondée sur la superficie dans le cadre d'un modèle d'optimisation dynamique normatif pour l'agriculture irriguée à partir des eaux souterraines. Le cadre conceptuel

Canadian Journal of Agricultural Economics 58 (2010) 433–461
DOI: 10.1111/j.1744-7976.2010.01199.x

modélise les décisions d'adoption du producteur en présence d'incertitude tout en tenant compte de l'influence des technologies d'irrigation comme intrants quasi fixes, c'est-à-dire, l'influence de la fixité des actifs sur les décisions d'adoption du producteur. Dans ce modèle, la production végétale totale est fondée sur l'évapotranspiration d'eau d'irrigation tandis que l'aspect coût est fondé sur la quantité totale d'eau appliquée.

INTRODUCTION

Irrigated agriculture accounts for nearly half the value of U.S. crop sales and 80–90% of consumptive water use in the United States. However, competition for the use of agricultural water supplies has intensified. Population growth, ecological and environmental demands, and Native American water right claims[1] continue to drive water resource conflicts in many western States. More recently, climate change projections and water demands for a growing biofuels sector are placing new pressures on existing water allocations, heightening awareness of the importance of water conservation in irrigated agriculture. Many factors—producer, farm, economic, institutional, and environmental—influence irrigation water management and technology-adoption decisions and their effect on Federal water conservation and water quality goals. Climate change and energy sector growth, in particular, raise important questions: (1) Can irrigated agriculture adjust to climate-adjusted water supplies and emerging water demands through adoption of conserving technologies, water management practices, and/or crop shifts alone? (2) What changes in water institutions may be needed to complement water conservation policy to more effectively manage increasingly scarce water supplies for agriculture? And (3) how will these changes impact irrigated agriculture, resource use, the environment, and rural economies?

This paper first presents the policy motivation for examining continued producer adoption of conserving irrigation technologies as a foundation for providing a sustainable future for western irrigated agriculture. Second, we summarize the historical transitions that help define the adjustment path to increased sustainability within western irrigated agriculture. Third, we develop a new conceptual framework for groundwater management that endogenizes both per acre applied water and an acreage-based technology adoption relationship, with adoption decisions modeled under uncertainty within a normative, dynamic economic model for groundwater irrigated agriculture. Traditional dynamic-optimization approaches for groundwater management considered only aggregate water use as the policy management (control) variable (Brown and Deacon 1972; Gisser and Sanchez 1980; Feinerman and Knapp 1983; Gisser 1983; Worthington et al 1985; Kim and Moore 1989; Provencher and Burt 1993), or aggregate water demand by crop (Kim et al 1989). Our model extends the traditional approach by endogenizing both per acre water use and crop and technology-specific acreage allocations as control variables in response to water price changes. Endogenizing irrigation water use in this way, our model expands the producer technology choice set beyond the traditional irrigation system definition to include irrigation water management (i.e., *deficit irrigation*) as a crop production technology choice.[2] Furthermore, our framework also models consideration of irrigation technology as a quasi-fixed input, i.e., the model considers the influence of asset fixity on producer irrigation technology adoption decisions by accounting for their dynamic adjustment costs.[3] Accounting for endogenous technical change under uncertainty that incorporates both physical system and water management dimensions, as well as producer technology adoption adjustment costs, will: (1) improve measures of producer behavioral response to shifting water-supply conditions expected due to drought, climate change, and emerging water demands; (2) expand our ability to evaluate the impacts of alternative conservation/water management strategies in response to increasingly scarce water supplies; and (3) improve upon measurements of social welfare benefits and costs of alternative public water resource policies. These measurement improvements can facilitate optimal water resource reallocation by helping public decision makers differentiate between the need for improved water conservation policy versus institutional change in water resource management. Finally, we conclude the paper by providing summary comments and potential policy implications.

STUDY MOTIVATION

New pressures on regional water budgets have refocused attention on the increasing scarcity of water resources in the western United States and the sustainable use of water for irrigated agriculture. Climate change is expected to continue to alter both the supply and the demand for water throughout the West for all sectors, while energy sector growth, particularly for biofuels production, is also expected to increase demand for water resources. Of the two, climate change is likely to have the more dramatic impact. Water demand for a biofuel plant of a given size is generally known (an engineering relationship) and local (site-specific). This direct water demand is generally managed through market-based permanent lease or purchase agreements among known farms and the biofuel firm of interest.[4] On the other hand, climate change is expected to have a broader, and potentially more insidious impact on agriculture (while it is known to exist, it is not readily quantifiable from year to year), by affecting all of agricultural production (including all irrigated production).

Global climate change has been occurring for some time and is expected to continue well into the future. In the western United States, a gradual warming of temperatures is expected to significantly shift the West's traditional source of freshwater supplies from winter precipitation (i.e., snowpack) to more frequent and intense early spring precipitation falling as rain (Knowles et al 2006; IPCC Report 2007). This shift is expected to dramatically alter the quantity and timing of associated stream flows, with more flow occurring in the early spring, reducing quantities available for reservoir storage (from reduced late spring and summer snowmelt), thereby reducing water supplies available to meet traditional peak irrigation water demands in the summer and fall. Studies conducted for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC Report 2007) reveal that: (1) the fraction of annual precipitation falling as rain (rather than snow) increased at 74% of weather stations studied in the western mountains of the United States from 1949 to 2004 (Knowles et al 2006); (2) April 1 snowwater equivalent snow cover has declined 15 to 30% since 1950 in the western mountains of North America (Mote et al 2003, 2005; Lemke et al 2007); and (3) in the central Rocky Mountain region, streamflow over the last century has decreased by about 2% per decade (Rood et al 2005).

River basin–specific studies indicate that expected increases in future warming trends are expected to exacerbate these water resource impacts. For the Upper Colorado River Basin (UCRB), Christensen and Lettenmaier (2007) applied forecasted changes in temperature and precipitation from 11 climate models and report an 8–11% decrease in UCRB runoff by the end of the 21st century. Hoerling and Eischeid (2007), after examining 42 climate simulations for the UCRB, report likely average decreases in UCRB streamflow of 25% by 2030, and 45% by 2060. McCabe and Wolock (2007), using a combined approach, including analyses based on a multi-century tree-ring reconstruction (1490–1998) of streamflow for the Colorado River basin and climate model simulations, report that warming temperatures (from 1° to 2 °C) would reduce mean water-year flows for the UCRB from 8 to 17%, respectively. They suggest that such flow changes would increase the likelihood of failure to meet the water allocation requirements of the Colorado River Compact. Van Kirk and Naman (2008), accounting for increased irrigation withdrawals and consumptive use over time, estimate that 39% of the observed decline in the July–October discharge of the Scott River within the Klamath River Basin is explained by regional-scale climatic factors. Furthermore, the authors conclude that these climate-induced decreases in late-summer streamflow will, at best, complicate the recovery of anadromous salmonids, and may, at worst, hinder their persistence. Climate change induced streamflow impacts will both directly and indirectly impact irrigation water supplies throughout the West, through reduced streamflows, as well as through increased competition for an increasingly scarce resource.

Groundwater, the primary water source for much of Plains States irrigated agriculture and a supplemental water supply (during low-precipitation/drought years) for many other irrigated areas of the West, will also likely be affected by climate change. In a study conducted for the National Oceanographic and Atmospheric Administration and the National Science Foundation, Dettinger and Earman (2007) found that while there is a need for more extensive study, continued warming will thin snowpacks and raise snowline elevations, and mountain recharge rates can be expected to decline as recharge areas shrink and snowmelt available for soil infiltration declines. Hall et al (2008) indicate that climate change can be expected to reduce aquifer recharge and water table levels, especially for shallow aquifers, because higher temperatures will increase evapo-transpiration (ET), and with more precipitation occurring as rain subject to increased runoff, less will be available to percolate into aquifers. They reveal that for the Ogallala aquifer region, groundwater recharge is expected to decrease by more than 20% if temperatures increase by 4.5 °F (2.4 °C) (IPCC Report 2007). For the Ellensburg Basin of the Columbia Basin Plateau, aquifer recharge rates could decrease by as much as 25% (NWAG Report 2000).

For the northern-tier western States, moderate warming conditions could potentially enhance ET efficiency for many crops, while for the southern-tier western States, moderate warming temperatures will likely reduce crop ET efficiency (IPCC Report 2007; CCSP 2008). Reduced crop ET efficiency will increase irrigation water demand; while for the more temperate regions, improved ET efficiency could reduce irrigation water demand. However, even for the northern-tier States, moderate warming conditions will likely still impact applied irrigation water demands, because with less water supply (due to reduced snowpack and more early-spring extreme rainfall events), irrigation timing of limited water supplies becomes a more critical crop/water management issue. With even higher climate change induced temperatures, such conditions are expected to intensify and expand geographically the impact climate change will have on irrigation water demands.

The critical linkage between climate change vulnerability and the sustainability of western irrigated agriculture is most likely *adaptability* (Wall and Smit 2005; IPCC Report 2007; Hall et al 2008; Brekke et al 2009). Reduced water supplies due to climate change will further constrain already over-allocated water resources across the western United States through increased competition, particularly among agricultural, municipal, industrial, and ecological uses (IPCC Report 2007). This increase in competition underscores the importance of the timing of irrigation applications, i.e., being capable of applying more limited water supplies at the time and in the amount needed to meet consumptive-use requirements by crop growth stage. In addition, with rising temperatures, high-pressure sprinkler and traditional gravity irrigation systems become even less efficient due to higher application losses associated with increased evaporation. Given occurring and projected climate changes, adaptability of western irrigated agriculture toward a more sustainable future will involve more extensive integration of conserving sprinkler and gravity irrigation systems with intensive infield water management practices. Such practices may include the use of soil- or plant-moisture sensing devices, commercial irrigation scheduling services, and computer-based crop growth simulation models that assist producers in deciding when and how much to irrigate.[5] Other practices useful for gravity-flow systems may include the use of tailwater pits, laser leveling of fields, shortening of furrow lengths, use of alternate row irrigations, reductions in irrigation set times, and use of polyacrylamide (PAM) (a water-soluble soil amendment that stabilizes soil and waterborne sediment), all practices that improve distributional uniformity, timing, and water reuse. For both sprinkler and gravity conserving irrigation systems, more intensive use of infield water management practices enhances a producer's ability to apply a quantity of water much closer to a crop's consumptive-use requirement at the time required for a given crop growth stage. Appropriately integrating water management practices with varied conserving irrigation systems broadens irrigated agriculture's adaptability, while enhancing long-run sustainability.

HISTORICAL TRANSITIONS IN IRRIGATION TECHNOLOGY/WATER MANAGEMENT IN THE WEST

Prior to the 1970s, furrow and flood irrigation systems were the dominant production systems for western irrigated agriculture. By 1978, sprinkler irrigation—including center-pivot systems—accounted for about 35% of crop irrigation in the West. Virtually all of this transition involved adoption of high-pressure sprinkler irrigation. While the center-pivot system improved infield irrigation efficiency, water conservation was not the primary motivation for its widespread adoption. Other factors, such as yield enhancement (due to enhanced field uniformity in applied water) or the ability to extend irrigated agriculture to productive lands (not suitable for a gravity system on account of topography or lands beyond traditional riparian boundaries), were the primary objectives behind the early transition from gravity-flow irrigation to center-pivot sprinkler irrigation. However, this expansion in irrigated agriculture brought with it additional problems, i.e., competitive resource allocation issues. With continued population growth in the West, the advent of the environmental age, and increased judicial efforts to honor Native American water rights, significant water policy analyses since the early 1980s have recognized the merits of new regulatory, conservation, and water market policies designed to mitigate water resource allocation conflicts (Howe 1985; Martin 1986; Hornbaker and Mapp 1988; Hamilton et al 1989; Kim et al 1989; Moore 1991; Schaible 2000; Peterson et al 2003; Schaible and Aillery 2003). But producers themselves, with assistance from Federal and State resource conservation programs, have adopted conserving irrigation production systems to improve irrigation returns, enhance the health and productivity of their resource base, and ensure a more sustainable future for their livelihoods.

Using data from the Farm and Ranch Irrigation Survey (FRIS) compiled over two decades (NASS 1984–2003), we evaluate technology transitions in western irrigated agriculture. Generally, this involves transitions from conventional irrigation systems of comparatively low water-use efficiency[6] to increased adoption of more water and energy conserving irrigation systems. The FRIS data are used to summarize: (1) irrigated acres and agricultural water use for three alternative definitions of "conserving irrigation" and (2) producer adoption of conserving water management practices. Alternative definitions for conserving gravity (GRV) irrigation systems, from least to most conserving, include:

Conserving GRV-1—furrow gravity irrigated acres with water distributed at the head of the field using an above- or below-ground pipe, or a lined open-ditch field-water delivery system.

Conserving GRV-2—gravity irrigated acres in GRV-1, plus acres for flood irrigation (*between borders or within basins*) for farms using laser-leveling, and using an above- or below-ground pipe or lined open-ditch field-water delivery system.

Conserving GRV-3—gravity irrigated acres in GRV-1, plus *all* flood irrigated acres for farms using laser-leveling, and field water supplied through an above- or below-ground pipe or lined open-ditch field-water delivery system.

Separately, for each of these definitions, all other gravity-flow irrigated acres were classified as consistent with a conventional gravity irrigation system.

The three alternative definitions for conserving pressure-sprinkler (SPK) irrigation systems, from least to most conserving, include:

Conserving SPK-1—acres irrigated using only drip/trickle irrigation systems.

Conserving SPK-2—acres irrigated in SPK-1, plus acres irrigated using low-pressure sprinkler irrigation systems (PSI < 30).

Conserving SPK-3—acres irrigated in SPK-1, plus acres irrigated using either low- or medium-pressure sprinkler irrigation systems (PSI < 60).

Separately, for each of these definitions, all other pressure-sprinkler irrigated acres were classified as consistent with a conventional pressure-sprinkler irrigation system. For gravity and pressure-sprinkler irrigation, respectively, GRV-1 and SPK-1 are designed to reflect a lower-bound for conserving irrigation, while GRV-3 and SPK-3 reflect an upper-bound.

Results for both conserving gravity and conserving pressure-sprinkler irrigation for FRIS survey years (from 1994 through 2003) are summarized in Table 1 (for acres irrigated) and Table 2 (for agricultural water use).[7] Results highlight several significant transitions that have occurred in irrigated acres, technology, and water use over the past 25 years in western irrigated agriculture. Of the 39.1 million acres irrigated in 1984, 62.0%

Table 1. Irrigated acres for the 17 western states by alternative conserving irrigation definition: FRIS data (1984–2003)

	Irrigated Acres	Gravity as a % of Tot. Farm Irr. Ac.	Spkr. & Drip/Tr as a % of Tot. Farm Irr. Ac.	Irrigated Acres by Conserving Irrigation Definition [Acres and Percent (%)] for:		
				Conserving Definition 1[a]	Conserving Definition 2[a]	Conserving Definition 3[a]
1984:						
Total Farm Irrigated Acres	39,097,612					
Total Gravity Irrigated Acres	24,084,966	62.0			NA[b]	
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres	14,657,800		37.0			
1988:						
Total Farm Irrigated Acres	37,996,825					
Total Gravity Irrigated Acres	22,731,136	60.0			NA[b]	
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres	14,991,394		39.0			
1994:						
Total Farm Irrigated Acres	38,958,806					
Total Gravity Irrigated Acres	20,344,444	52.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres	18,500,862		47.0			
Conserving Gravity Irrigation (Acres)				7,569,428	8,226,094	8,239,126
(*% of Total Gravity Irr. Acres*)				37.0	40.0	40.0
Conserving Pressure Irrigation (Acres)				1,082,603	6,009,732	10,673,081
(*% of Total Pressure Irr. Acres*)				6.0	32.0	58.0

(*Continued*)

Table 1. Continued

	Irrigated Acres	Gravity as a % of Tot. Farm Irr. Ac.	Spkr. & Drip/Tr as a % of Tot. Farm Irr. Ac.	Irrigated Acres by Conserving Irrigation Definition [Acres and Percent (%)] for:		
				Conserving Definition 1[a]	Conserving Definition 2[a]	Conserving Definition 3[a]
1998:						
Total Farm Irrigated Acres	39,049,840					
Total Gravity Irrigated Acres	19,164,703	49.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres	19,664,875		50.0			
Conserving Gravity Irrigation (Acres)				7,757,830	9,836,685	9,888,122
(*% of Total Gravity Irr. Acres*)				40.0	51.0	52.0
Conserving Pressure Irrigation (Acres)				1,193,636	9,084,497	15,332,970
(*% of Total Pressure Irr. Acres*)				6.0	46.0	78.0
2003:						
Total Farm Irrigated Acres	40,689,339					
Total Gravity Irrigated Acres	16,983,062	41.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres	24,210,083		58.0			
Conserving Gravity Irrigation (Acres)				5,887,767	6,874,244	6,892,057
(*% of Total Gravity Irr. Acres*)				35.0	41.0	41.0
Conserving Pressure Irrigation (Acres)				1,989,632	10,870,546	19,145,052
(*% of Total Pressure Irr. Acres*)				8.0	45.0	79.0

Source: National Agricultural Statistics Service (1984–2003). Farm and Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), USDA, Washington, DC.

Notes: [a]See the text for the three separate definitions for conserving gravity and pressure (sprinkler and drip/trickle) irrigation.

[b]NA = Not available. FRIS surveys for 1984 and 1988 did not collect sufficient data to summarize acres by conserving gravity and conserving sprinkler irrigation groups.

Table 2. Water use for the 17 western states by alternative conserving irrigation definition: FRIS data (1984–2003)

	Water Use (Acre Feet)	Gravity Irr. as a % of Tot. Farm Wat. Use	Spkr. & Drip/Tr as a % of Tot. Farm Wat. Use	Water Use by Conserving Irrigation Definition [Acre Feet and Percent (%)] for: Conserving Definition 1[a]	Conserving Definition 2[a]	Conserving Definition 3[a]
1984:						
For Total Farm Irrigation	74,274,390					
For Total Gravity Irrigation	52,986,925	71.0			NA[b]	
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation	20,972,520		28.0			
1988:						
For Total Farm Irrigation	72,887,539					
For Total Gravity Irrigation	50,008,499	69.0			NA[b]	
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation	22,704,890		31.0			
1994:						
For Total Farm Irrigation	70,487,278					
For Total Gravity Irrigation	45,140,601	64.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation	25,247,291		36.0			
For Conserving Gravity Irrigation (Ac.Ft.)				11,977,815	13,685,132	13,751,255
(*% of Total Water for Gravity Irr.*)				27.0	30.0	30.0
Conserving Pressure Irrigation (Ac.Ft.)				2,605,233	9,447,041	15,994,460
(*% of Total Water for Pressure Irr.*)				10.0	37.0	63.0

(*Continued*)

Table 2. Continued

	Water Use (Acre Feet)	Gravity Irr. as a % of Tot. Farm Wat. Use	Spkr. & Drip/Tr as a % of Tot. Farm Wat. Use	Water Use by Conserving Irrigation Definition [Acre Feet and Percent (%)] for:		
				Conserving Definition 1[a]	Conserving Definition 2[a]	Conserving Definition 3[a]
1998:						
For Total Farm Irrigation	76,183,611					
For Total Gravity Irrigation	45,520,419	60.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation	30,076,454		39.0			
For Conserving Gravity Irrigation (Ac.Ft.)				14,546,833	20,204,447	20,311,466
(*% of Total Water for Gravity Irr.*)				32.0	44.0	45.0
Conserving Pressure Irrigation (Ac.Ft.)				3,034,801	15,048,799	24,586,739
(*% of Total Water for Pressure Irr.*)				10.0	50.0	82.0
2003:						
For Total Farm Irrigation	75,891,901					
For Total Gravity Irrigation	39,580,780	52.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation	36,103,124		47.0			
For Conserving Gravity Irrigation (Ac.Ft.)				12,708,433	16,198,908	16,251,971
(*% of Total Water for Gravity Irr.*)				31.0	41.0	41.0
Conserving Pressure Irrigation (Ac.Ft.)				5,150,726	18,268,082	30,677,094
(*% of Total Water for Pressure Irr.*)				14.0	51.0	85.0

Source: National Agricultural Statistics Service (1984–2003). Farm and Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), USDA, Washington, DC.

Notes: [a]See the text for the three separate definitions for conserving gravity and pressure (sprinkler and drip/trickle) irrigation.

[b]NA = Not Available. FRIS surveys for 1984 and 1988 did not collect sufficient data to summarize water use by conserving gravity and conserving sprinkler irrigation groups.

were irrigated with a gravity-flow system. By 2003, total irrigated acres had expanded by 1.6 million acres and total agricultural water use by 1.6 million acre-feet. Of the 40.7 million acres irrigated, only 41.0% were irrigated with gravity-flow irrigation; pressure-sprinkler irrigation had captured nearly 60% of the area irrigated in the West.

Tables 1 and 2 also reveal a shift in the type of irrigation technology used across western irrigated agriculture. FRIS survey data indicate that more recently (since 1994) irrigation technology transitions in the West have shifted, with more emphasis on technology transitions occurring from acreage using improved gravity-flow systems (e.g., furrow systems using piped or lined open-ditch field-water delivery) to acreage using more conserving pressure-sprinkler irrigation systems (low-pressure sprinkler, low-energy precision application, and drip/trickle systems). Between 1994 and 1998, results show that adoption of improved gravity-flow systems continued to increase for each of the conserving-gravity irrigation definitions (Table 1). For the broadest conserving definition (GRV-3), improved gravity-irrigated acreage increased from 40.0 to 52.0% of all gravity-flow irrigated acres. During the same time period, improved pressure-sprinkler irrigation increased from 58.0 to 78.0% of all pressure-sprinkler irrigated acres. However, from 1998 to 2003, the share of gravity-flow irrigated acres using improved gravity irrigation systems declined for each of the conserving-gravity definitions. Consistently, improved pressure-sprinkler irrigated acres also continued to increase, although at a slower rate than in the earlier period. Table 2 results, identifying relative shares in water use by conserving technology definition over time, illustrate a similar shift in recent technology transitions across western irrigated agriculture. From a policy perspective, these shifts are likely important, in that, a slowing of the transition from conventional gravity-flow irrigation to improved pressure-sprinkler irrigation may be attributable to some threshold beyond which existing conservation policy incentives may be less effective (particularly as it relates to transitions from conventional gravity to improved pressure-sprinkler irrigation).

Table 3 results show that for gravity irrigation, and for irrigated agriculture in general across the West, producers continue to rely more extensively on the use of conventional infield water management practices. For gravity irrigation, producers tend to give more emphasis to such conventional practices as reducing irrigation set times, irrigating only alternate furrows (for row crops), and using end-of-field dikes to restrict field runoff. Other, more conserving gravity-flow management practices have either declined in use, or have received little producer attention. Use of tailwater pits to enhance on-farm water reuse (and thereby reduce the need for additional withdrawals) has declined across gravity irrigation, from a high of 22.0% in 1994 to 8.0% in 2003. Use of laser-leveled acres for gravity irrigation has declined from a high of 27.0% in 1998 to 16.0% in 2003. In addition, by 2003, other conserving gravity management practices, such as the use of special furrowing techniques, shortened furrow lengths, and PAM, represent a relatively small portion of present-day westwide gravity irrigated agriculture.

Table 3 results also show that despite technological advances in crop/soil moisture sensing, irrigated crop producers in the West continue to depend heavily on the use of more conventional methods in deciding when to irrigate a crop, and by how much. Most producers generally irrigate based on the visible "condition of the crop," or by "feeling the soil" (for its moisture content), or irrigation may be tied to a calendar schedule or simply whenever water is delivered "in-turn" to the farm. Fewer than 8.0% of irrigators throughout the West use soil- or plant-moisture sensing devices or commercial

Table 3. Use of water management practices for the 17 western states, across FRIS survey years

	1984	1988	1994	1998	2003
Total number of irrigated farms (farms)	179,473	180,525	149,351	147,090	174,936
Total gravity irrigated acres (acres)	24,084,966	22,731,136	20,344,444	19,164,703	16,983,062
Methods Used in Deciding When to Irrigate					
			Percent (%) of Irrigated Farms		
Use of any method (use of one or more of the decision methods below)	96.0	94.0	96.0	99.0	100.0
Condition of the crop	26.0	69.0	66.0	70.0	77.0
Feel of the soil	40.0	36.0	37.0	40.0	34.0
Use of soil-moisture sensing devices	8.0	8.0	9.0	8.0	7.0
Use of commercial scheduling services	3.0	5.0	3.0	4.0	7.0
Use of media reports	4.0	4.0	3.0	5.0	8.0
Based on the schedule of water delivery to the farm	13.0	13.0	18.0	12.0	15.0
Based on a calendar schedule	18.0	18.0	20.0	20.0	21.0
Use of computer simulation models	NA	NA	3.0	1.0	1.0
Use of plant-moisture sensing devices	NA	NA	NA	NA	2.0
Irrigate when the neighbors begin to irrigate	NA	NA	NA	NA	7.0
Water Management Practices Used with Gravity-Flow Irrigation Systems:					
			Percent (%) of Gravity Irrigated Acres		
Tailwater pits	NA	20.0	22.0	12.0	8.0
Surgeflow/cablegation irrigation	NA	5.0	4.0	4.0	2.0
Special furrowing techniques	NA	12.0	12.0	6.0	6.0
Shortening of the furrow length	NA	NA	5.0	3.0	3.0
Reducing irrigation set times	NA	NA	13.0	13.0	15.0
Using alternate row irrigations	NA	NA	17.0	15.0	12.0
Use of polyacrylamide (PAM)	NA	NA	NA	2.0	2.0
Restricting runoff by diking end of field	NA	NA	NA	NA	13.0
Use of mulch or other type of row cover	NA	NA	NA	NA	1.0
Laser-leveled acres	NA	10.0	21.0	27.0	16.0

Source: National Agricultural Statistics Service (1984–2003). Farm and Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), USDA, Washington, DC.
Notes: NA = Not available. FRIS surveys for these years did not collect data for these decision methods or water management practices.

irrigation scheduling services. Fewer than 2.0% of producers use computer-based simulation models designed to evaluate crop irrigation requirements based on crop growth stage consumptive-use needs given local weather conditions.

So, even with the substantial technological innovation that has already occurred in western irrigated agriculture, there likely still exists significant room for improvement (Schaible 2004). The historical transitions suggest that while western irrigated agriculture is on a path toward greater sustainability, it nevertheless has not been fully attained.

MODEL DEVELOPMENT

Technology Adoption for Groundwater Irrigated Agriculture

Given that climate change forecasts predict both significant reductions in future water-supply resources, and increases in evaporation and crop ET requirements in much of the western United States, infield water management intensity will become significantly more important. As the transition to higher-efficiency physical systems wanes, there will be a need for greater policy emphasis on water management intensity to achieve Federal/State conservation policy goals for a sustainable irrigated agricultural sector in the West. Because of generally declining aquifer levels, this will likely be no more truer than for groundwater irrigated agriculture throughout much of the West.

While groundwater irrigated agriculture makes use of similar irrigation systems and water management practices as does surface-water irrigated agriculture, accounting for producer use of groundwater and groundwater management is unique. The cost structure for groundwater use/management involves a dynamic relationship that must account for increased pumping costs associated with declining aquifer table levels over time and increased resource opportunity costs associated with a common-pool property. The literature assessing the merits of groundwater use/management for irrigated agriculture is extensive. Traditional studies have made use of dynamic-optimization (optimal control) models that account for unique aquifer hydrologic characteristics to endogenize an aquifer's time-dependent resource opportunity value for agriculture (appropriate references are cited in paragraph two of the introduction). The models for these studies, however, fall short when one needs to analyze groundwater use/management issues that account for restricted water supplies due to climate change. The need for emphasis on more intensive use of on-farm water management practices, including deficit irrigation, as well as accounting for acreage shifts due to profitability changes associated with rising resource costs highlights the importance of a modeling framework that disaggregates the traditional aggregate water demand relationship. Crop-specific per acre water application and production system-based technology-specific acreages become the driving forces necessary to effectively evaluate the benefits of groundwater use/management for irrigated agriculture under a climate change environment.

Kim et al (1997, 2000) and Kim and Schaible (2000) extend the traditional dynamic-optimization framework for groundwater use/management by first disaggregating water use, recognizing both its consumptive use and applied water use components.[8] Second, we further extend this modeling framework, endogenizing crop- and technology-specific per acre water use (disaggregated between consumptive and applied water use), as well as a conceptual framework for an acreage-based technology adoption model—a decision framework reflecting the ability of producers to account for the potential benefits and costs associated with producer adoption of improved irrigation production technology under uncertainty. The decision framework recognizes that the adoption of an improved irrigation production system (technology) is no certainty, but rather, we assume that the time to adopt an improved irrigation technology is uncertain and we therefore incorporate the risks of the timing of adoption within our framework. Furthermore, in this dynamic decision framework we recognize irrigation technology as a quasi-fixed input, and as such, the need to constrain the decision framework to reflect the influence of asset fixity. That is, we endogenize within the decision framework the dynamic adjustment cost reflecting producer recognition of the opportunity cost associated with the "fixity" of irrigation technologies once they have been adopted. However, we also recognize that various barriers (e.g., limited producer management skills, lack of financial resources, producer age, farm size, unique soil or agri-environmental conditions, or other reasons) prevent some irrigators from adopting improved irrigation technologies. For example, some pastures are often irrigated with gravity-based, unlined ditch water-delivery systems. With a high-priority water right and relatively minor water costs, such producers are unlikely to alter their irrigation technology. Therefore, recognizing the unique nature of asset fixity applied to irrigation production systems, we establish a per acre water use and acreage-based technology adoption model within a dynamic decision framework for groundwater irrigated agriculture, both with and without dynamic adjustment costs for asset fixity. Modeling crop-specific per acre water use and technology-specific acreage (with and without dynamic adjustment costs) and technology-specific investment as control variables, one can more effectively evaluate the benefits of producer production system response to both resource price and supply changes, as well as for policy-induced resource changes.

We begin by specifying a consumptive-use based crop production function. So, let the per acre production for the ith crop, (y_i), be a quadratic such that

$$y_i(W_i) = a_{i0} + a_{i1}W_i - a_{i2}W_i^2, \quad (i = 1, 2, \ldots, n) \tag{1}$$

where $\frac{\partial y_i}{\partial W_i} > 0$, $\frac{\partial^2 y_i}{\partial W_i^2} < 0$, and where $a_{i0,}$ $a_{i1,}$ and a_{i2} are nonnegative parameters, and W_i represents the ith crop per acre consumptive-use component of irrigation water (in units of acre-feet of pumped groundwater for the irrigated crop).

Assume that the irrigation-efficiency relationship for water applied using the jth irrigation technology is given by

$$W_i = k_{ij}W_{ij}, \quad \text{for all } i \text{ and } j, \text{ and } 0 < k_{ij} \leq 1 \tag{2}$$

where k_{ij} represents the rate of applied irrigation efficiency associated with the ith crop production and the jth irrigation technology, and W_{ij} is the actual rate of irrigation water applied (per acre) for the ith crop and the jth irrigation technology. The per acre crop production relationship presented in Equation (1) can be restated as

$$y_{ij}(k_{ij}W_{ij}) = a_{i0} + a_{i1}[k_{ij}W_{ij}] - a_{i2}[k_{ij}W_{ij}]^2 \tag{3}$$

where y_{ij} is the ith crop yield per acre for the jth irrigation technology.

Now, let total production for the ith crop be represented by

$$Y_i = \sum_{j=1}^{m} y_{ij}(k_{ij} W_{ij})\ A_{ij}\left(\frac{P_w}{P_{y_i}}\right),\ \ \frac{\partial A_{ij}}{\partial P_w} < 0;\ \frac{\partial A_{ij}}{\partial P_{y_i}} > 0 \tag{4}$$

where A_{ij} is the acreage for the ith crop and the jth irrigation technology,[9] P_w is pumping cost per acre-foot of groundwater, and P_{y_i} is a unit output price for the ith crop.

Next, recognizing that not all irrigators will adopt an improved irrigation production system, we establish the profit and net social benefit relationships for: (A) the case with no dynamic cost adjustment, and (B) the case endogenizing dynamic adjustment cost associated with asset fixity.

(A) **Case of no dynamic cost adjustment**.

Let the total profit function relationship be specified as

$$\pi = \sum_{i}^{n} P_{y_i} Y_i - P_w \sum_{i}^{n} \sum_{j}^{m} W_{ij} \tag{5}$$

where total crop production (output) is based on consumptive use of irrigation water, and the cost side is based on total applied water (Kim et al 1997; Kim and Schaible, 2000). The inverse irrigation water demand for the ith crop and the jth irrigation technology is then derived as follows:

$$\begin{aligned} P_w &= P_{y_i}\left(\frac{\partial Y_i}{\partial W_{ij}}\right) \\ &= \alpha_{ij} A_{ij} - 2\beta_{ij} A_{ij} W_{ij} \quad \text{for } i = 1, 2, \ldots,\ n \end{aligned} \tag{6}$$

where $\alpha_{ij} = P_{y_i}(1 + \frac{\varepsilon_{ij}\eta_{ij}}{\phi_{ij}})k_{ij}a_{i1}$ and $\beta_{ij} = P_{y_i}(1 + \frac{\varepsilon_{ij}\eta_{ij}}{\phi_{ij}})k_{ij}^2 a_{i2}$ are parameters of the irrigation water demand function, and where $\varepsilon_{ij} = (\frac{\partial A_{ij}}{\partial Pw})(\frac{Pw}{A_{ij}})$ represents an acreage response elasticity, $\eta_{ij} = (\frac{\partial Pw}{\partial W_{ij}})(\frac{W_{ij}}{Pw})$ represents the price flexibility of water demand, and $\phi_{ij} = (\frac{\partial y_{ij}}{\partial W_{ij}})(\frac{W_{ij}}{y_{ij}})$ represents the output elasticity for water (all for the ith crop and jth irrigation technology).

We can now evaluate a measure for the net social benefits of an increase in pumping cost for groundwater irrigation. To begin, the social benefits (SB) resulting from irrigation water use are represented by

$$\begin{aligned} \text{SB} &= \sum_{i}^{n} \sum_{j}^{m} \int_0^{W_{ij}} \int_0^{A_{ij}} k_{ij}[\alpha_{ij} z_{ij} - 2\beta_{ij} z_{ij} x_{ij}]\ dz_{ij} dx_{ij} \\ &= 0.5 \sum_{i}^{n} \sum_{j}^{m} k_{ij}\left[\alpha_{ij} A_{ij}^2 W_{ij} - \beta_{ij} A_{ij}^2 W_{ij}^2\right] \end{aligned} \tag{7}$$

where x_{ij} and z_{ij} are variables of integration. Total pumping costs (TC) across crops and irrigation technologies are represented by

$$\mathrm{TC} = \sum_{i}^{n} \sum_{j}^{m} [C(SL - h) A_{ij} W_{ij}] \tag{8}$$

where C = pumping cost per acre-foot of water per foot of lift, SL = the elevation in feet of the field surface level above sea level, and h = the water table elevation in feet above sea level.

Then the net social benefits (NSB) for groundwater irrigation across crops and irrigation technologies are represented by Equation (9), as follows:

$$\mathrm{NSB} = 0.5 \sum_{i}^{n} \sum_{j}^{m} \left[\alpha_{ij} k_{ij} A_{ij}^2 W_{ij} - 2C(SL - h) A_{ij} W_{ij} - \beta_{ij} k_{ij} A_{ij}^2 W_{ij}^2\right] \tag{9}$$

(B) **Case of dynamic cost adjustment.**

Under dynamic adjustment costs associated with asset fixity (Epstein 1981; Vasavada and Ball 1988), the per acre profit function is represented by

$$\pi^* = \sum_{i}^{n} P_{y_i} Y_i^* - P_w \sum_{i}^{n} \sum_{j}^{m} W_{ij}^* - \sum_{j}^{m} q_j K_j \tag{10}$$

where q_j is the rental price of the jth quasi-fixed input K_j (an advanced irrigation technology), such that $\frac{\partial K_j}{\partial t} = (\mathrm{I}_j - \boldsymbol{\gamma} K_j)$, where γ is a constant depreciation rate and I represents investment. Assuming the value function is quadratic (Epstein 1981), the inverse irrigation water demand function is linear and represented as follows:

$$\begin{aligned} P_w &= [(a_0 + a_{1j}\, q_{1j}) + (a_{2j} - a_{3j}\boldsymbol{\gamma})K_j - d_j I_j]\ A_{ij}^* - 2\mathrm{b}_{ij}\mathrm{A}_{ij}^*\mathrm{W}_{ij}^* \\ &= [a_{ij} - c_j K_j - d_j I_j]\mathrm{A}_{ij}^* - 2b_{ij} A_{ij}^* \mathrm{W}_{ij}^* \quad \text{for} \quad i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, m \end{aligned} \tag{11}$$

where a, b, c, and d are constants, and $a_{ij} = (a_0 + a_{1j}\, q_{1j})$ and $c_j = (\mathrm{a}_{2j} - \mathrm{a}_{3\mathrm{j}}\boldsymbol{\gamma})$.

The social benefits (SB*) resulting from groundwater use for irrigation with asset fixity are represented by

$$\begin{aligned} \mathrm{SB}^* &= \sum_{j}^{m} \sum_{i}^{n} \int_0^{W_{ij}^*} \int_0^{A_{ij}^*} \int_0^{I_j} k_{ij}[[a_{ij} - c_j K_j - d_j u_j]v_{ij} - 2b_{ij} v_{ij} w_{ij}]\, du_j dv_{ij} dw_{ij} \\ &= 0.5 \sum_{j}^{m} \sum_{i}^{n} k_{ij} \left\{[(a_{ij} - c_j K_j) - \ 0.5 d_j\ I_j]\ I_j\ \ A_{ij}^{*2} W_{ij}^* - b_{ij} I_j\ \ A_{ij}^{*2} W_{ij}^{*2}\right\} \end{aligned} \tag{12}$$

Total costs for groundwater use that include both pumping costs and rental values for the quasi-fixed inputs are represented by

$$\mathrm{TC}^* = \sum_{j}^{m}\left(\sum_{i}^{n}\left[C(SL-h)A_{ij}^{*}W_{ij}^{*} + q_j K_j\right]\right) \tag{13}$$

The net social benefits (NSB*) resulting from groundwater use for irrigation across crops, irrigation technologies, and dynamic adjustment costs are then represented by

$$\begin{aligned}\mathrm{NSB}^* = 0.5\sum_{j}^{m}\sum_{i}^{n}\ &\{[k_{ij}((a_{ij} - \ c_j K_j) - 0.5 d_j I_j) I_j A_{ij}^{*2} \\ &- 2C(SL-h)A_{ij}^{*}]W_{ij}^{*} - 2q_j K_j - k_{ij} b_{ij} I_j A_{ij}^{*2} W_{ij}^{*2}\}\end{aligned} \tag{14}$$

The dynamic-optimization model that endogenizes acreage for the ith crop production and the jth irrigation technology with and without adjustment costs is presented as follows[10]:

$$\begin{aligned}\text{Max Z} = 0.5\int_{t=0}^{T} e^{-rt}\sum_{j}^{m}\sum_{i}^{n}&\{(1-F)[k_{ij}a_{ij}A_{ij}^{2}W_{ij} - 2C(SL-h)A_{ij}W_{ij} - k_{ij}\beta_{ij}A_{ij}^{2}W_{ij}^{2}] \\ &+ \ F[[k_{ij}((a_{ij} - c_j K_j) - 0.5 d_j I_j)\ I_j A_{ij}^{*2} - 2C(SL-h)A_{ij}^{*}]W_{ij}^{*} \\ &- 2q_j K_j - k_{ij} b_{ij} I_j A_{ij}^{*2} W_{ij}^{*2}]\}dt\end{aligned} \tag{15}$$

subject to the following constraints[11,12]:

$$\frac{\partial h(t)}{\partial t} = \frac{R + (\delta - 1)\left\{N + \sum_{i}^{n}\sum_{j}^{m}\left[(1-F)A_{ij}W_{ij} + F\left(A_{ij}^{*}W_{ij}^{*}\right)\right]\right\}}{E \bullet S} \tag{16}$$

$$\frac{\partial F(t)}{\partial t} = f(C(SL-h),\ q_j K_j)[1 - F(t)], \quad (j = 1,\ 2, \ldots,\ m) \tag{17}$$

$$\frac{\partial K_j}{\partial t} = (I_j - \boldsymbol{\gamma} K_j), \quad (j = 1, 2, \ldots, m) \tag{18}$$

$$A_{ij} = \exp\left\{\sigma_0 + \sigma_{ij} D_{ij}\left[\frac{C(SL-h)}{P_{yi}}\right]\right\}, \text{(for } i = 1,\ 2, \ldots,\ n \text{ and } j = 1,\ 2, \ldots,\ m) \tag{19}$$

$$A_{ij}^{*} = \exp\left\{s_0 + s_{ij} D_{ij}\left[\frac{C(SL-h) + \varepsilon_{ij} q_j K_j}{P_{yi}}\right]\right\}, \text{ (for } i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots, m) \tag{20}$$

$$h(t = 0) \; = \; h_0 \tag{21}$$

where T is the terminal time period, $F(t)$ represents the probability of adoption of an improved irrigation production technology at time t where $F(t = 0) = 0$ (see Appendix for further discussion), the variable N in Equation (16) represents the amount of groundwater allocated for Native Americans, h_0 represents the initial water table level, $R =$ the aquifer recharge rate, $\delta =$ the rate of return flow, E is the size of the aquifer (measured in acres), S is a storativity coefficient for the aquifer, t is a time variable, r is the discount rate, and ε_{ij} is a fractional coefficient.

Farmers' decisions to invest in an advanced irrigation technology depends on the level of groundwater pumping costs and the investment adjustment costs as shown in Equation (A1) of Appendix. As pumping costs increase, the probability that farmers make investments in advanced irrigation technologies would increase, while higher adjustment costs would discourage farmers from making such investments. When farmers do not make the investment in an advanced irrigation technology, i.e., the probability F in the objective function (Equation (15)) equals zero, the objective function considers only conventional irrigation technologies. When all farmers are considered to make the investment in advanced irrigation technologies, i.e., F equals one, the objective function then considers only the dynamic cost adjustment associated with asset fixity.

The Lagrangian-Hamiltonian equation for our dynamic model is represented as follows:

$$\begin{aligned}
H = {} & 0.5\, e^{-rt} \sum_j^m \sum_i^n \{(1 - F)[k_{ij}\alpha_{ij} A_{ij}^2 W_{ij} - 2C(SL - h) A_{ij} W_{ij} - k_{ij}\beta_{ij} A_{ij}^2 W_{ij}^2] \\
& + F[(k_{ij}(a_{ij} - c_j K_j - 0.5 d_j I_j)\; I_j \;\; A_{ij}^{*2} - 2C(SL - h) A_{ij}^{*}) W_{ij}^{*} - 2q_j K_j \\
& - k_{ij} b_{ij} I_j \;\; A_{ij}^{*2} W_{ij}^{*2}]\} \\
& + \lambda_1(t) \left[\frac{R + (\delta - 1)\left\{ N + \sum_j^m \sum_i^n [(1 - F)\cdot A_{ij} W_{ij} + F(A_{ij}^{*} W_{ij}^{*})] \right\}}{E \bullet S} \right] \\
& + \lambda_2(t)\; f(C(SL - h),\; q_j K_j)[1 - F(t)] + \lambda_3(t)(I_j - \boldsymbol{\gamma} K_j) \\
& + \sum_j^m \sum_i^n \phi_{ij} \left[A_{ij} - \exp\left\{ \sigma_0 + \sigma_{ij} D_{ij} \left(\frac{C(SL - h)}{P_{yi}} \right) \right\} \right] \\
& + \sum_j^m \sum_i^n \phi_{ij}^{*} \left[\mathrm{A}_{ij}^{*} - \exp\left\{ s_0 + s_{ij} D_{ij} \left(\frac{C(SL - h) + q_j K_j}{P_{yi}} \right) \right\} \right]
\end{aligned} \tag{22}$$

where λ_i ($i = 1, 2, 3$) are adjoint variables associated with state variables h, F, and K; and where W_{ij}, W_{ij}^{*}, A_{ij}, A_{ij}^{*}, and I_j ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) are control variables, and ϕ_{ij}^{*} and $\phi_{ij}$are Lagrangian multipliers associated with producer acreage response functions with and without quasi-inputs, respectively.

The necessary conditions for optimality, which hold for all i and j, are given as follows:

$$\frac{\partial H}{\partial W_{ij}} = e^{-rt}[0.5k_{ij}\alpha_{ij}A_{ij} - C(SL-h) - k_{ij}\beta_{ij}A_{ij}W_{ij}](1-F)A_{ij} + \lambda_1(t)\left[\frac{(\delta-1)(1-F)A_{ij}}{E \bullet S}\right]$$
$$= 0 \quad (\text{for } i = 1, 2, \ldots, n; \text{ and } j = 1, 2, \ldots, m) \tag{23-1}$$

$$\frac{\partial H}{\partial W^*_{ij}} = e^{-rt}\left\{0.5[k_{ij}(a_{ij} - c_jK_j - 0.5d_jI_j)\, I_j A^{*2}_{ij} - 2C(SL-h)A^*_{ij}\right] - k_{ij}b_{ij}I_jA^{*2}_{ij}W^*_{ij}\big\}F$$
$$+\lambda_1(t)\left[\frac{(\delta-1)F\mathrm{A}^*_{ij}}{E \bullet S}\right] = 0 \quad (\text{for } i = 1, 2, \ldots, n; \text{ and } j = 1, 2, \ldots, m) \tag{23-2}$$

$$\frac{\partial H}{\partial A_{ij}} = e^{-rt}[k_{ij}\alpha_{ij}A_{ij} - C(SL-h) - k_{ij}\beta_{ij}A_{ij}W_{ij}](1-F)W_{ij} + \lambda_1(t)\left[\frac{(\delta-1)(1-F)W_{ij}}{E \bullet S}\right]$$
$$+\phi_{ij} = 0 \quad (\text{for } i = 1, 2, \ldots, n; \text{ and } j = 1, 2, \ldots, m) \tag{23-3}$$

$$\frac{\partial H}{\partial A^*_{ij}} = e^{-rt}\left\{[k_{ij}(a_{ij} - c_jK_j - 0.5d_jI_j)\mathrm{I}_jA^*_{ij} - C(SL-h)]W^*_{ij} - k_{ij}b_{ij}I_jA^*_{ij}W^{*2}_{ij}\right\}F$$
$$+\lambda_1(t)\left[\frac{(\delta-1)FW^*_{ij}}{E \bullet S}\right] + \phi^*_{ij} = 0 \quad (\text{for } i = 1, 2, \ldots, n; \text{ and } j = 1, 2, \ldots, m) \tag{23-4}$$

$$\frac{\partial H}{\partial I_j} = 0.5\mathrm{e}^{-rt}\left[k_{ij}(a_{ij} - c_jK_j - d_jI_j)\, A^{*2}_{ij}\mathrm{W}^*_{ij} - k_{ij}b_{ij}A^{*2}_{ij}W^{*2}_{ij}\right]F + \lambda_3 = 0$$
$$(\text{for } i = 1, 2, \ldots, n; \text{ and } j = 1, 2, \ldots, m) \tag{23-5}$$

$$-\frac{\partial H}{\partial h} = -e^{-rt}\sum_j^m\sum_i^n\left[(1-F)CA_{ij}W_{ij} + 0.5FCA^*_{ij}W^*_{ij}\right] - \lambda_2(1-F)\left(\frac{\partial f}{\partial h}\right)$$
$$-\sum_j^m\sum_i^n\left[\phi_{ij}A_{ij}\left(\frac{\sigma_{ij}CD_{ij}}{P_{yi}}\right) + \phi^*_{ij}A^*_{ij}\left(\frac{s_{ij}CD_{ij}}{P_{yi}}\right)\right] = \frac{\partial\lambda_1}{\partial t} \tag{23-6}$$

$$
\begin{aligned}
-\frac{\partial H}{\partial F} = 0.5e^{-rt}\sum_{i}^{n}\sum_{j}^{m}\Big\{&\big[k_{ij}\alpha_{ij}A_{ij}^{2}W_{ij} - 2C(SL-h)A_{ij}W_{ij} - k_{ij}\beta_{ij}A_{ij}^{2}W_{ij}^{2}\big] \\
&-\big[k_{ij}(a_{ij} - c_j K_j - 0.5d_j I_j)\ I_j A_{ij}^{*2} - 2C(SL-h)A_{ij}^{*}\big]W_{ij}^{*} - 2q_j K_j - k_{ij}b_{ij}I_j A_{ij}^{*2}W_{ij}^{*2}\Big\} \\
&+\lambda_1\frac{(\delta-1)\sum_{j}^{m}\sum_{i}^{n}\big[A_{ij}W_{ij} - A_{ij}^{*}W_{ij}^{*}\big]}{E\bullet S} + \lambda_2 f(C(SL-h),\ q_j K_j) = \frac{\partial\lambda_2}{\partial t}
\end{aligned} \tag{23-7}
$$

$$
\begin{aligned}
-\frac{\partial H}{\partial K_j} = 0.5e^{-rt}\sum_{i}^{n}\big[Fk_{ij}c_j I_j A_{ij}^{2}W_{ij}^{*} + 2q_j\big] - \lambda_2(t)q_j\left(\frac{\partial f}{\partial K_j}\right)(1-F) + \lambda_3\gamma \\
+\sum_{i}^{n}\phi_{ij}^{*}A_{ij}^{*}\left(\frac{s_{ij}q_j D_{ij}}{P_{yi}}\right) = \frac{\partial\lambda_3}{\partial t}
\end{aligned} \tag{23-8}
$$

$$
\frac{\partial H}{\partial\lambda_1} = \left[\frac{R + (\delta-1)\left[N + \sum_{j}^{m}\sum_{i}^{n}\left((1-F)\cdot A_{ij}W_{ij} + F\left(A_{ij}^{*}W_{ij}^{*}\right)\right)\right]}{E\bullet S}\right] = \frac{\partial h}{\partial t} \tag{23-9}
$$

$$
\frac{\partial H}{\partial\lambda_2} = f(C(SL-h),\ q_j K_j)[1-F(t)] = \frac{\partial F}{\partial t} \tag{23-10}
$$

$$
\frac{\partial H}{\partial\lambda_3} = (I_j - \boldsymbol{\gamma}K_j) = \frac{\partial K}{\partial t} \tag{23-11}
$$

$$
\frac{\partial H}{\partial\phi_{ij}} = \left[A_{ij} - \exp\left\{\sigma_0 + \sigma_{ij}D_{ij}\left(\frac{C(SL-h)}{P_{yi}}\right)\right\}\right] \le 0 \ \text{ and } \ \phi_{ij}\left(\frac{\partial H}{\partial\phi_{ij}}\right) = 0 \tag{23-12}
$$

$$
\frac{\partial H}{\partial\phi_{ij}^{*}} = \left[A_{ij}^{*} - \exp\left\{s_0 + s_{ij}D_{ij}\left(\frac{C(SL-h) + \varepsilon_{ij}q_j K_j}{P_{yi}}\right)\right\}\right] \le 0 \quad \text{and} \quad \phi_{ij}^{*}\left(\frac{\partial H}{\partial\phi_{ij}^{*}}\right) = 0 \tag{23-13}
$$

$$
\lim_{t\to T}\lambda_1 = 0,\ \lim_{t\to T}\lambda_2 = 0,\ \lim_{t\to T}\lambda_3 = 0,\ \lim_{t\to T}\lambda_1 h = 0,\ \lim_{t\to T}\lambda_2 F = 0,\ \lim_{t\to T}\lambda_3 K = 0 \tag{23-14}
$$

Equation (23-1) assures that the optimal water use for a particular conventional irrigation technology equates the marginal benefits of irrigation water to its marginal pumping costs plus the marginal user costs associated with irrigation water use. When fixed quasi-assets are considered, Equation (23-2) explains that the marginal social benefits of irrigation water with an improved technology equal the sum of its marginal pumping costs and the marginal user costs associated with groundwater use for irrigation. Equation (23-3) equates the marginal social benefits of an acreage allocation with conventional irrigation technology to the sum of its marginal pumping costs, marginal user costs associated with groundwater use for irrigation, and the opportunity costs associated with the acreage allocation decision. When investment for adopting an advanced irrigation technology is made, Equation (23-4) explains that the marginal social benefits of irrigation water equal the sum of its marginal pumping costs and the marginal user costs associated with groundwater use for irrigation.

By summing Equations (23-1) and (23-2), the results can be presented as follows:

$$
\begin{aligned}
&e^{-rt}\{[0.5k_{ij}\alpha_{ij}A_{ij} - C(SL-h) - k_{ij}\beta_{ij}A_{ij}W_{ij}](1-F)A_{ij}\} \\
&\quad + \left\{0.5\left[k_{ij}(a_{ij} - c_jK_j - 0.5d_jI_j)I_jA_{ij}^{*2} - 2C(SL-h)A_{ij}^{*}\right] - k_{ij}b_{ij}I_j\ A_{ij}^{*2}W_{ij}^{*}\right\}F \\
&\quad = -\lambda_1(t)\left\{\left[\frac{(\delta-1)(1-F)A_{ij}}{E\bullet S}\right] + \left[\frac{(\delta-1)F\mathrm{A}_{ij}^{*}}{E\bullet S}\right]\right\} \\
&\qquad\qquad (\text{for } i = 1, 2, \ldots, n;\ \text{and } j = 1,\ 2, \ldots,\ m)
\end{aligned} \tag{24-1}
$$

At optimum, Equation (24-1) explains that the total expected (weighted) marginal net profits of groundwater use for irrigation must equal its total expected (weighted) user costs of groundwater use. Similarly, the sum of Equations (23-3) and (23-4) can be represented as follows:

$$
\begin{aligned}
&e^{-rt}\left\{[k_{ij}\alpha_{ij}A_{ij} - C(SL-h) - k_{ij}\beta_{ij}A_{ij}W_{ij}](1-F)W_{ij} + \left[k_{ij}(a_{ij} - c_jK_j - 0.5d_jI_j)I_jA_{ij}^{*}\right.\right. \\
&\quad \left.\left. - C(SL-h)\right]W_{ij}^{*} - k_{ij}b_{ij}I_jA_{ij}^{*}W_{ij}^{*2}\right\}F = -\lambda_1(t)\left\{\left[\frac{(\delta-1)(1-F)W_{ij}}{E\bullet S}\right] + \left[\frac{(\delta-1)FW_{ij}^{*}}{E\bullet S}\right]\right\} \\
&\quad - \left(\phi_{ij} + \phi_{ij}^{*}\right) \quad (\text{for } i = 1, 2, \ldots, n;\ \text{and } j = 1, 2, \ldots, m)
\end{aligned} \tag{24-2}
$$

Equation (24-2) explains that the expected (weighted) marginal benefits of land allocation must equal the sum of the expected (weighted) marginal user costs and acreage-allocation opportunity costs. Equation (23-5) explains that the adjoint variable $\lambda_3$represents the expected marginal social benefits of the capital investment.

Equation (23-6) represents the adjoint equation reflecting the fact that groundwater pumping creates the value associated with user cost. Equation (23-7) represents the adjoint equation explaining that the decision to invest or not for an advanced irrigation technology creates the economic costs (shadow values). Equation (23-8) represents the adjoint equation reflecting that the investment to adopt a quasi-fixed asset creates the values associated with user costs. Equations (23-9) through (23-11) represent the equations of motion. Equations (23-12) and (23-13) represent the complementary slackness conditions for optimization. Equation (23-14) represents the conventional transversality conditions, which must hold in the limit as time approaches the terminal time T.

With W_{ij}, W^*_{ij}, A_{ij}, A^*_{ij}, and I_j as endogenous control variables, this framework can be used to evaluate the benefits of technology adoption for groundwater irrigated agriculture from a production system perspective. That is, irrigation production technologies are defined beyond the traditional irrigation application system definition such that they integrate on-farm water management practices as a component of the irrigation production system. In doing so, "deficit irrigation," an economic technology choice option given the greater likelihood of water-supply restrictions under climate change, also becomes a more relevant measurable instrument within a broader public policy, resource management tool kit. Being able to endogenize on-farm water management within watershed-level resource management under alternative climate change considerations enhances resource policy flexibility. This modeling framework provides the ability to address these broader water-based, resource management policy issues.[13]

SUMMARY AND CONCLUSIONS

In the past 25 years, irrigated agriculture in the West has made significant strides toward a more sustainable future. In recent years, conserving irrigation likely accounts for just under half of agricultural water use across the West (as defined in Table 2 using Conserving Definition 2). However, continued concerns over traditional nonagricultural water demands (associated with expected growth from municipal, industrial, environmental, and Native American water right claims) will likely be compounded by new demands induced through climate change and a growing biofuel energy sector. These emerging demands will increase pressures on the present allocation mechanism for an increasingly scarce resource, raising uncertainty about the prospects for sustainability of irrigated agriculture in the West. Climate change, likely to have the more dominant impact in many areas, raises policy questions about the factors affecting producer adoption of conserving irrigation production systems (including conserving physical systems as well as on-farm water management practices), and how western irrigated agriculture will achieve a sustainable future.

Because climate change, via warming temperatures, is expected to not only reduce the quantity and timing of water supplies, but to increase evaporation and crop ET requirements, on-farm water management will likely become much more critical to a sustainable future for irrigated agriculture in the West. Therefore, understanding the merits of producer irrigation technology adoption decisions from an irrigation production systems perspective, their policy implications, and their contribution to a sustainable future for western agriculture, requires an economic framework that can assess the benefits of irrigation technology change more complex than what traditional economic models were designed to address.

For this paper, we examined the historical transitions in irrigation technologies and water management practices across western U.S. agriculture. Results demonstrate that more than 50% of agricultural water use in the West continues to be applied through the use of less-efficient, conventional irrigation systems, implying that significant room likely still exists for improvement in on-farm water-use efficiency. This is even truer when one accounts for the efficiency improvement potential associated with more extensive adoption of more intensive on-farm water management practices (including deficit irrigation).

Given that climate change implies a need for more serious policy emphasis on integrated irrigation production systems, i.e., integrating on-farm water management with the adoption of conserving irrigation systems, in this paper we extend the dynamic-optimization framework for groundwater irrigation. Within this new theoretical framework we endogenize both per acre applied water and an acreage-based technology adoption relationship with the adoption decision framework modeled under uncertainty. In addition, technology adoption decisions are modeled accounting for the influence of asset fixity. However, because not all irrigators will adopt an innovative technology, adoption decisions for improved irrigation production systems are evaluated for the cases with and without accounting for dynamic adjustment costs due to asset fixity. Finally, within this dynamic framework, total crop production (output) is based on consumptive use of irrigation water while the cost side is based on total applied water. Endogenizing groundwater use in this way will improve upon the measurement of producer behavioral response to shifting water-supply conditions expected due to drought, climate change, and/or emerging water demands. We also expect that the modeling framework will expand our ability to evaluate the impacts of more broadly defined watershed-level integrated water management strategies, as well as improve upon measurements of social welfare benefits and costs of alternative public groundwater management policies. In addition, with improved impact measurements, the modeling framework proposed here can also facilitate optimal water resource policy with its capability to evaluate more flexible site-specific policies that help public decision makers differentiate between the need for improved water conservation policy versus institutional change in water resource management.

Finally, a logical extension for this work will involve an application of our model to a region that relies importantly on groundwater for crop production. Given that climate change is expected to directly impact both water supplies for agriculture and the efficiency of water use for all regions of the western States, and that bio-energy growth has been shifting to the Ogallala region, groundwater irrigated crop production across the Nebraska, Kansas, Wyoming, Colorado High Plains region would serve as an ideal test case to apply the model. However, at this time, we are waiting on the availability of data for USDA's 2008 FRIS, a detailed survey of 2008 farm-level irrigation production activities and farm water resource use for a sample of producers from the 2007 Census of Agriculture who indicated irrigation activity on their farm. The 2008 FRIS sample included 33,085 irrigated farms, consisting of 23,089 general crop production farms and 9,996 farms classified as horticultural farms. Unfortunately, the raw data for the 2008 FRIS were not available in time to apply our model for this paper. We expect that future research will apply this model using the 2008 FRIS for several western regions representing different agri-climatic and aquifer hydrologic environments.

ACKNOWLEDGMENTS

The authors thank the CJAE editor and reviewers for their many valued suggestions. We give special thanks to the reviewer for the valued insights and suggestions with respect to our model needing to account for quasi-asset fixity. However, the views expressed are the authors' and do not necessarily represent those of the Economic Research Service or the U.S. Department of Agriculture.

NOTES

[1]Native American water rights for Indian reservations are Federal reserved water rights, established by the U.S. Supreme Court with its 1908 *Winters v. U.S.* decision. The ruling established reserved rights for water that are necessary for Native Americans to maintain and survive on the land granted to the reservation by the government, even if those rights were not explicitly stated in the reservation Treaty. In subsequent decisions, the U.S. Supreme Court quantified these water rights as the water needed to irrigate all "practicably irrigable acreage" on the reservation, as well as making such rights generally superior to the rights of all other appropriators by vesting them with a "priority" date equivalent to the date of establishment of the reservation (Moore 1989; Gregory 2008). Potential Indian water right claims have been estimated at nearly 46 million acre-feet annually (Western States Water Council 1984), even though presently, the claims for many Indian reservations are under negotiation or remain unresolved within settlement disputes or judicial proceedings. While the Winters doctrine definitely applies to surface waters, the U.S. Supreme Court in 1976 (in *Cappaert v. U.S.*) opened the door for Indian reserved water right claims to apply to groundwater. While no definitive decision on Indian reserved rights to groundwater has been made, some States recognize these rights while others have not (Gregory 2008).

[2]Previous irrigation technology adoption studies defined producer irrigation technology decisions from an irrigation application system perspective, i.e., use of a flood or furrow-based gravity irrigation system versus a center-pivot sprinkler system (Caswell and Zilberman 1985; Lichtenberg 1989; Negri and Brooks 1990; Schaible and Aillery 2003). With available farm-level survey-based information we are now able to define irrigation technology decisions in broader conservation-relevant terms, i.e., from an irrigation production system perspective—one that integrates producer decisions on both field application system and field-level water management practices.

[3]We extended the decision framework to consider the influence of asset fixity on producer technology adoption decisions based on a reviewer suggestion.

[4]While total withdrawals for biofuel processing are comparatively low, regional/local impacts on water resources are more significant. A growing biofuels industry is expected to induce additional demand for water as producers respond to an increase in corn and soybean prices and expand irrigated corn and soybean acreage. Chiu et al (2009), in estimating the embodied water in ethanol by State (i.e., ethanol's lifecycle water use), reveal that: (1) more corn production for ethanol is taking place within highly irrigated regions, particularly in the northern High Plains Ogallala region; (2) consumptive water appropriation by bio-ethanol in the United States has increased 246% from 1.9 to 6.1 trillion liters between 2005 and 2008; and (3) for the Ogallala aquifer region, total consumptive water use for bio-ethanol (including water for irrigation) increased from 2.4 trillion liters in 2007 to 4.5 trillion liters in 2008 (of which about 68% was supplied from groundwater). The National Research Council (2008) estimated that: (1) irrigated corn for ethanol (in Nebraska) requires about 780 gallons of freshwater withdrawals per gallon of ethanol; and (2) while irrigation of native grass today would be unusual, this could easily change as cellulosic biofuel production gets under way. The U.S. Government Accountability Office, in its recent report (U.S. GAO 2009), estimates the average water consumed in corn ethanol production (adjusting for irrigation return flows) for the northern Plains States at 323.6 gallons of water per gallon of ethanol. Nearly 88% of this requirement is expected to come from groundwater.

[5]While the technologies and water management practices discussed here focus on on-farm conserving irrigation systems, we do recognize that the efficiency of irrigated agriculture may also be enhanced by improving the efficiency of water delivered to the farm gate from off-farm sources, through the lining of delivery canals, the use of pipelines rather than open, unlined delivery canals, and improvements in off-farm conveyance system management. However, addressing the issue of improvements in the efficiency of off-farm water delivery systems is beyond the scope of our research objectives for this paper.

[6]Water use efficiency here is interpreted to represent the fraction of applied water used to meet crop consumptive use and other beneficial purposes. Water applied but not used for beneficial purposes is regarded as field loss, some portion of which may eventually return to the hydrologic system through surface return flow and aquifer percolation.

[7]Data on conserving gravity and conserving pressure-sprinkler systems were inadequate to formulate consistent definitions of conserving irrigation for the 1984 and 1988 FRIS surveys. (In addition, FRIS results for 2008 will not be electronically available in time for this paper.)

[8]Traditional inter-temporal optimization models were inadequate for guiding groundwater management decisions because they measured economic benefits based on using only the rate of groundwater applied for irrigation, implying that all groundwater applied is totally consumed in the crop production process. However, changes in the groundwater stock and economic benefits are correctly measured when the crop production and hydrologic relationships within the modeling framework recognizes that not all groundwater applied is consumed by the crop. The rate of water applied generally exceeds the rate of crop consumptive use, with the difference generally defined as the rate of return flow (Kim et al 1997).

[9] $A_{ij}(y_{ij}) = \exp\{\sigma_0 - \sigma_{ij}\, D_{ij}\, (\frac{P_w}{P_{y_i}})\} + \varepsilon_j$ (derived from Schaible et al 2009).

[10]Following Fisher (1981, p. 70), we use a single social discount rate. Fisher explains that the essential idea is that consumption of an exhaustible resource "by future generations is a public good to members of the present generation." Furthermore, he observes that "This, in turn, implies . . . . that the social discount rate is below the private rate." The difference may vary over time due to economic situations, but it is most likely independent of pumping costs.

[11]Groundwater allocated for Native American water right claims (N) can be accounted for through their impact on aquifer hydrology, which ultimately affects farm-level groundwater pumping costs. We assume that a fixed portion of groundwater used by Native Americans for a region of interest would also return to the aquifer at the rate of the return flow, δ. (Similar adjustments can account for other nonagricultural water-use allocations.)

[12]The acreage response function presented in footnote 9 is rewritten here (and in Equations (19) and (20)) by replacing $P_w = C(SL-h)$ as follows: $A_{ij} = \exp\{\sigma_0 - \sigma_{ij} D_{ij}\, (\frac{C(SL-h)}{P_{yi}})\}$ when conventional irrigation technologies are used and ($A^*_{ij} = \exp\{s_0 - s_{ij} D_{ij} \frac{C(SL-h)+\varepsilon_{ij} q_j K_j}{P_{yi}}\}$) when an advanced irrigation technology (a quasi-fixed asset) is used.

[13]The data requirements for this modeling framework are more intensive than that required for the traditional optimal control framework for groundwater irrigation. To appropriately measure the benefits of production system-based technology adoption, behavioral data need to account for integrated producer crop and irrigation technology/water management specific decisions. USDA's 2008 FRIS captures this behavior. However, data for the 2008 FRIS will not be electronically available for research purposes until sometime in early to mid 2010.

REFERENCES

Brekke, L. D., J. E. Kiang, J. R. Olsen, R. S. Pulwarty, D. A. Raff, D. P. Turnipseed, R. S. Webb and K. D. White. 2009. *Climate Change and Water Resources Management—A Federal Perspective*, 65 pp. U.S. Geological Survey, Circular 1331.

Brown, G. and R. Deacon. 1972. Economic optimization of a single cell aquifer. *Water Resources Research* 8: 552–64.

Caswell, M. and D. Zilberman. 1985. The choices of irrigation technologies in California. *American Journal of Agricultural Economics* 67: 224–34.

Chiu, Y.-W., B. Walseth and S. Suh. 2009. Water embodied in bio-ethanol in the United States. *Environmental Science and Technology* 43 (8): 2688–92.

Christensen, N. S. and D. P. Lettenmaier. 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology & Earth System Sciences* 11 (July): 1417–34.

Climate Change Science Program (CCSP). 2008. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. CCSP and the Subcommittee on Global Change Research. Contributors: P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahn, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, R. Shaw, 362 pp. Washington, DC, USA: U.S. Dept. of Agriculture.

Dettinger, M. and S. Earman. 2007. Western groundwater and climate change—pivotal to supply sustainability or vulnerability in its own right? *Ground Water: News and Views* 4 (1) (June): 4–5.

Epstein, L. G. 1981. Duality theory and functional forms for dynamic factor demands. *Review of Economic Studies* 48 (1) (January): 81–95.

Feinerman, E. and K. Knapp. 1983. Benefits from groundwater management: Magnitude, sensitivity, and distribution. *American Journal of Agricultural Economics* 65: 703–10.

Fisher, A. C. 1981. *Resource and Environmental Economics*, 284 pp. Cambridge: Cambridge Surveys of Economic Literature, Cambridge University Press.

Gisser, M. 1983. Groundwater: Focusing on the real issue. *Journal of Political Economy* 91 (6) (December): 1001–27.

Gisser, M. and D. Sanchez. 1980. Competition versus optimal control in groundwater pumping. *Water Resources Research* 16: 638–42.

Gregory, L. 2008. "Technically open": The debate over Native American reserved groundwater rights. *Journal of Land, Resources, and Environmental Law* 28 (2): 361–73.

Hall, N. D., B. B. Stuntz and R. H. Abrams. 2008. Climate change and freshwater resources. *Natural Resources & Environment* 22 (3) (Winter): 30–35.

Hamilton, J. R., N. K. Whittlesey and P. Halverson. 1989. Interruptible water markets in the Pacific northwest. *American Journal of Agricultural Economics* 71: 63–75.

Hoerling, M. and J. Eischeid. 2007. Past peak water in the southwest. *Southwest Hydrology* 6 (1): 18–19, 35.

Hornbaker, R. H. and H. P. Mapp. 1988. A dynamic analysis of water savings from advanced irrigation technology. *Western Journal of Agricultural Economics* 13: 307–15.

Howe, C. W. 1985. Economic, legal, and hydrologic dimensions of potential interstate water markets. *American Journal of Agricultural Economics* 67: 1226–30.

IPCC Report. 2007. Climate change 2007: Impacts, adaptation and vulnerability. Contributions of Working Group II to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, J. P. van der Linden, and C. E. Hanson, 976 pp. Cambridge, UK: Cambridge University Press.

Kieffer, N. M. 1988. Economic duration data and hazard functions. *Journal of Economic Literature* 26: 646–79.

Kim, C. S. and M. R. Moore. 1989. *Public Policies in Water-Resource Use: Their Effect on Groundwater Mining and Surface-Water Imports*, Technical Bulletin, No. 1764, Economic Research Service, U.S. Department of Agriculture, 35 pp.

Kim, C. S. and G. D. Schaible. 2000. Economic benefits resulting from irrigation water use: Theory and an application to groundwater use. *Environmental & Resource Economics* 17: 73–87.

Kim, C. S., G. D. Schaible and S. G. Daberkow. 2000. An efficient cost-sharing program to reduce nonpoint-source contamination: Theory and an application to groundwater contamination. *Environmental Geology* 39 (6) (April): 649–59.

Kim, C. S., M. R. Moore, J. J. Hanchar and M. Nieswiadomy. 1989. A dynamic model of adaptation to resource depletion: Theory and an application to groundwater mining. *Journal of Environmental Economics & Management* 17: 66–82.

Kim, C. S., C. Sandretto, R. Fleming and R. Adams. 1997. An alternative specification for modeling groundwater dynamics. *Natural Resource Modeling* 10: 173–83.

Kim, C. S., G. D. Schaible, J. Lewandrowski and U. Vasavada. 2010. Managing invasive species in the presence of endogenous technological change with uncertainty. *Risk Analysis* 30 (2): 250–60.

Knowles, N., M. D. Dettinger and D. R. Cyan. 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate* 19 (18) (September): 4545–59.

Lemke, P. J., R. R. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fuji, G. Kaser, P. Mote, R. H. Thomas and T. Zhang. 2007. Observations: Changes in snow, ice and frozen ground. In *Climate Change 2007: The Physical Science Basis, a contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Quin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, pp. 337–84. Cambridge and New York: Cambridge University Press.

Lichtenberg, E. 1989. Land quality, irrigation development, and cropping patterns in the northern high plains. *American Journal of Agricultural Economics* 71: 187–94.

Martin, W. E. 1986. Evolving water institutions in an urbanizing west: Discussion. *American Journal of Agricultural Economics* 68: 1152–54.

McCabe, G. J. and D. M. Wolock. 2007. Warming may create substantial water supply shortages in the Colorado river basin. *Geophysical Research Letters* 34, L22708 (November): 1–5.

Moore, M. R. 1989. Native American water rights: Efficiency and fairness. *Natural Resources Journal* 29 (Summer): 763–91.

Moore, M. R. 1991. The Bureau of Reclamation's new mandate for irrigation water conservation: Purposes and policy alternatives. *Water Resources Research* 27 (2) (February): 145–55.

Mote, P. W., A. F. Hamlet, M. P. Clark and D. P. Lettenmaier. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86: 39–49.

Mote, P. W., E. A. Parson, A. F. Hamlet, W. S. Keeton, D. Lettenmaier, N. Mantau, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter and A. K. Snover. 2003. Preparing for climate change: The water, salmon, and forests of the Pacific northwest. *Climate Change* 61: 45–88.

National Agricultural Statistics Service (NASS). **1984–2003.** *Farm and Ranch Irrigation Survey (1984, 1988, 1994, 1998, 2003)*. Washington, DC: Analyses conducted by ERS through the NASS Data Lab, U.S. Department of Agriculture.

National Research Council. **2008.** *Water Implications of Biofuels Production in the United States*, ISBN: 0-309-11362–8, Water Science and Technology Board, National Academy of Sciences, 86 pp.

Negri, D. H. and D. H. Brooks. 1990. Determinants of irrigation technology choice. *Western Journal of Agricultural Economics* 15: 213–23.

NWAG Report. **2000.** *Water: The Potential Consequences of Climate Variability and Change*. A Report of the National Water Assessment Group for the U.S. Global Change Research Program [Lead Author: Peter Gleick], Pacific Institute, Oakland, CA (September), 160 pp.

Peterson, J. M., T. L. Marsh and J. R. Williams. 2003. Conserving the Ogallala aquifer: Efficiency, equity, and moral motives. *Choices* 1st Quarter: 15–18.

Provencher, B. and O. Burt. 1993. The externalities associated with the common property exploitation of groundwater. *Journal of Environmental Economics & Management* 24: 139–58.

Rood, S. B., G. M. Samuelson, J. K. Weber and K. A. Wyrot. 2005. Twentieth-century decline in streamflows from the hydrographic apex of North America. *Journal of Hydrology* 306: 215–33.

Rose, N. L. and P. L. Joskow. 1990. The diffusion of new technologies: Evidence from the electric utility industry. *Rand Journal of Economics* 21: 354–73.

Schaible, G. D. 2000. Economic and conservation tradeoffs of regulatory vs. incentive-based water policy in the Pacific northwest. *International Journal of Water Resources Development* 16 (2): 221–38.

Schaible, G. D. 2004. *Western Irrigated Agriculture*. Washington, DC: Economic Research Service, USDA. Electronic Data Product. http://www.ers.usda.gov/Data/WesternIrrigation (accessed June 15, 2010).

Schaible, G. D. and M. P. Aillery. 2003. Irrigation technology transitions in the mid-plains states: Implications for water conservation/water quality goals and institutional changes. *International Journal of Water Resources Development* 19 (1): 67–88.

Schaible, G. D., D. M. Lambert, C. S. Kim and S. Stefanova. 2009. Structural conservation practices in U.S. wheat production: A cost-function technology adoption approach. *Journal of Natural Resources Policy Research* 1 (2) (April): 167–88.

U.S. Government Accountability Office (GAO). 2009. *Energy-Water Nexus: Many Uncertainties Remain about National and Regional Effects of Increased Biofuel Production on Water Resources*, GAO-10–116 (a report to Chairman, Committee on Science and Technology, U.S. House of Representatives), 50 pp.

Van Kirk, R. W. and S. W. Naman. 2008. Relative effects of climate and water use on base-flow trends in the lower Klamath basin. *Journal of American Water Resources Association* 44 (4) (August): 1035–52.

Vasavada, U. and V. E. Ball. 1988. A dynamic adjustment model for U.S. agriculture: 1948–79. *Agricultural Economics* 2: 123–37.

Wall, E. and B. Smit. 2005. Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture* 27 (1): 113–23.

Western States Water Council. 1984. *Indian Water Rights in the West*. A study prepared for the Western Governors Association (May), Denver, Colorado.

Worthington, V. E., O. R. Burt and R. L. Brustkern. 1985. Optimal management of a confined groundwater system. *Journal of Environmental Economics & Management* 12: 229–45.

APPENDIX

Economic benefits associated with the use of groundwater for irrigation depend largely on whether the innovative irrigation technology is adopted. Once farmers decide to adopt an improved technology, they must pay the rental costs over the period of time of using this technology (i.e., adjustment costs). The hazard function has been widely used for studying the adoption of an improved technology (Kieffer 1988; Rose and Joskow 1990; Kim et al 2010). Therefore, we let $F(t)$ be the probability of the adoption of an improved technology at time t where $F(t = 0) = 0$. The conditional probability of adopting a new technology at time t, f $(C(SL\text{-}h), qK)$, is the probability that adoption of such an improved irrigation technology will occur during the next time period, $t + \Delta t$, given that a new technology has not been adopted at time t. We assume that the time to adopt an improved irrigation technology is uncertain, but that the likelihood of adopting a new irrigation technology is expressed as follows:

$$f(C(SL - h),\ qK) = \left(\frac{\partial F(t)/\partial t}{1 - F(t)}\right) \tag{A1}$$

where $f(C(SL - h(t = 0)), qK_0) = 0$, $\frac{\partial f}{\partial h} < 0$, $\frac{\partial f}{\partial (qK)} < 0$, and $\frac{\partial F(t)}{\partial t}$ is the probability density function.

Equation (A1) can be rewritten as a state equation for adopting an improved irrigation technology as follows:

$$\frac{\partial F(t)}{\partial t} = f(C(SL - h),\ qK)[1 - \ F(t)] \tag{A2}$$

where $F(t) = 1 - \ e^{-f(C(SL-h),\, qK)t}$.

The state Equation (A2) associated with the timing of adopting an improved irrigation technology will be incorporated into our optimal control model of groundwater use for irrigation.